in all the years prior to 1900, and 90 percent in this century. Humans have become energy-hungry. The U.S. Navy's Admiral Hyman G. Rickover has stated this clearly:

> Our country with only 5 percent of the world's population uses one-third of the world's total energy input; this proportion would be even greater except that we use energy more efficiently than other countries. Each American has at his disposal each year energy equivalent to that obtainable from 8 tons of coal. This is six times the world's per capita energy consumption. With high energy consumption goes a high standard of living. Thus, the enormous energy from fuels feeds machines which make each of us master of an army of mechanical slaves. Man's muscle power is rated at $\frac{1}{35}$ horsepower continuously. Machines furnish every American industrial worker with energy equivalent to that of 244 men, while the equivalent of at least 2000 men push each automobile along the road, and every family is supplied with 33 faithful household helpers. Each locomotive engineer controls energy equivalent to that of 100,000 men; each jet pilot (that) of 1 million men. Truly the humblest American enjoys the services of more slaves than were once owned by the richest nobles, and lives better than most ancient kings. In retrospect, and despite wars, revolutions, and disasters the 100 years gone by may well seem like the 'Golden Age.'

Most energy generation involves the conversion of some type of fuel, usually by combustion. Temperature is the driving force for energy conversion, so it is usually an important variable. Table 4.1 indicates the approximate continuous temperature associated with various conversion processes.

PROJECTED ENERGY DEMANDS

There are many study groups whose function is to predict the future demand for energy. One of these, The National Petroleum Council, initially projected U.S. energy consumption to increase at an average rate of 4.2 percent per year between 1971 and 1985. This value proved

***Table* 1.1** High-Temperature Sources

Source	Temp., Continuous, K	Remark on Temperature
Bunsen burner	1400	
Blowtorch	1900	
Controlled nuclear reaction	3000	Limited by construction materials
Oxyacetylene flame	3380	Hottest low-cost chemical flame available
Combustion of aluminum powder in pure oxygen	3800–4400	Theoretical maximum; pressure 0.1 and 1 MPa, respectively
Solar furnace	4000	Maximum estimated
Combustion of carbon subnitride	5000–6000	Maximum estimated
Electrical induction furnace	to 5000	Limited by crucible construction materials
Plasma arc	2000–50,000	Depends on arc type and current

SOURCE: *Ind. Eng. Chem.* 55 (1) 18 (1963).

to be much too high. Balzhizer[1] reviewed the predictions made by various professional groups and showed that as a result of the unforeseen extraordinary price changes brought about by the Organization of Petroleum Exporting Countries (OPEC) and U.S. government restrictions on burning high-sulfur fuels, such predictions have become largely meaningless at this time. Brown[2] has also observed the failure of recent predictions and notes the effect on demand of severe changes in price. Figure 1.1, which is based on several sources, shows actual energy consumption in recent years and indicates reasonable predictions for the future. Because industry is becoming far more energy-efficient, such predictions must be regarded with suspicion. Making future plans for the production and use of energy has become very questionable.

Conservation

Energy had been kept artificially cheap in the United States until the drastic OPEC price rise and the increasing ratio of imported oil to domestic oil forced U.S. prices to approach world levels.

Space heating, transportation, and industry are the major users of energy. Industry has responded rapidly to the huge increases (nearly tenfold between 1973 and 1981) in energy costs, reducing its energy consumption yearly while the gross national product continued to increase. Figure 1.2 shows the interesting trend in industrial use of energy. Transportation has been far less responsive to prices, although the effect of smaller, fuel-efficient cars is just now beginning to show. Space heating, residential and commercial, will require considerable capital investment and new and innovative design to reduce requirements markedly; these will be slow in coming, although some slight improvement has already appeared. Conservation at all levels is absolutely essential if prices are to be maintained at any reasonable level.

[1]Balzhizer, U.S. Energy Prospects, *Chem. Eng.* 89 (2) 74 (1982).

[2]Brown, The U.S. Energy Outlook through the Year 2000, *Chem. Eng. Prog.* 77 (9) 9 (1981).

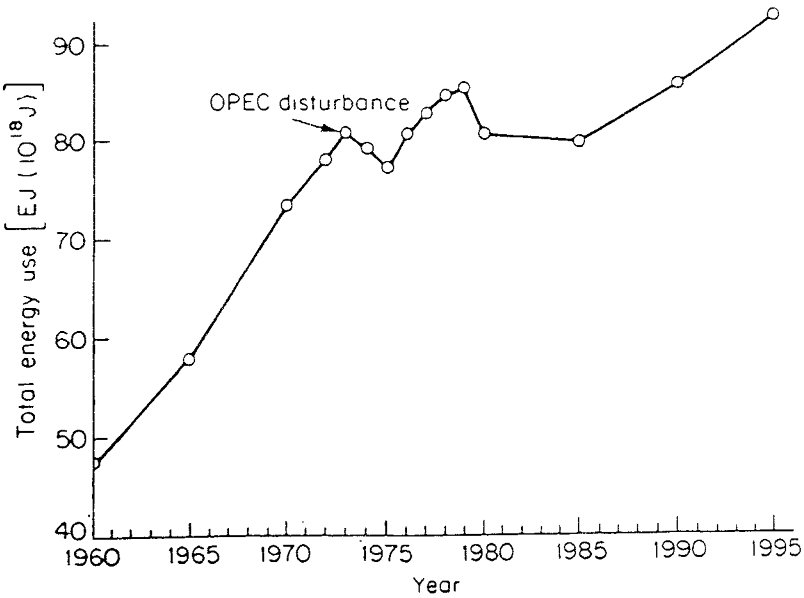

Fig. 1.1. U.S. energy consumption.

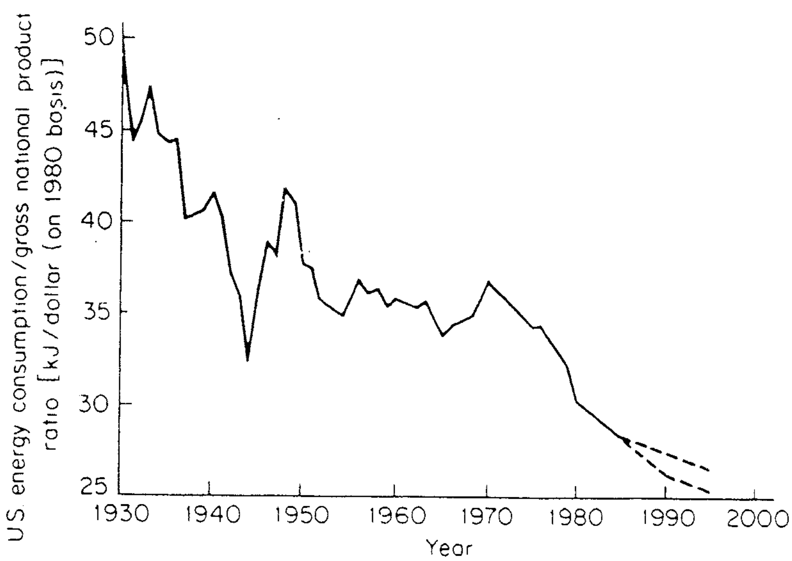

Fig. 1.2. Energy consumption ratio against gross national product, in 1980 dollars

Competitive Energy Sources

Fossil fuels and geothermal, wind, solar, tidal, human, animal, and nuclear energies are all competitive so local conditions may make one of them superior. Energy must be generated or collected inexpensively for broad general use, and Table 1.2 is an attempt to estimate costs relative to coal as of 1982. Many alternate forms of energy are of small interest because of the large investment required for a slow and erratic return. Some are inconvenient to the users or are unreliable.

FOSSIL FUELS

Fossil fuels are solids, liquids, and gases. Prices vary locally depending on abundance and competition. Competition is distorted by environmental considerations and particularly by government regulations. The abnormally low price of natural gas, regulated by the U.S. government, has led to the use of this fine, clean-burning fuel for uses for which less desirable fuels, such as coal and residual oil, would have been equally suitable. Major effort is now being expended toward better methods of coal combustion (fluidized bed combustion in the presence of limestone, flue gas scrubbers, and other pollution control systems) which result in less contamination of the atmosphere. The desire to reduce sulfur oxides in the air has led to regulations reducing the use of high-sulfur residual oils and eastern coals, however.

Solid Fuels

PEAT. Peat (wet, partially decomposed organic matter) deposits are worked in other parts of the world, but are unlikely to become a significant power source in the United States because the energy content per unit of weight is not great, deposits are mainly in isolated areas, and the drying problem is severe. There are extensive horticultural uses for peat.

Table 1.2 Cost of Energy for Home and Transport Use

Source of Energy	Price, $/GJ
Bituminous coal	4.3
Fuel oil	6.2
Crude oil	6.2
Natural gas	4.5
Biomass, direct combustion	1–3
Peat	1–3
Syncrude from tar sands	4.3
Producer gas	2–5
Biogas	2–12
Charcoal	5–13
Shale oil	4.3–6.1
Ethanol from biomass	15.9–32.7
Methanol from biomass	12.9–23.8
Vegetable oils	24.8–59.5
Geothermal	1.5–2
Passive solar	1
Solar panel	1.6
Solar flat plate collector (30 to 90°C)	5–20
Nuclear	5.5
Wind	Insufficiently developed to estimate, dominated by fixed charges of $200–$600 per kilowatt of installed capacity
Water power	Varies widely, generally very low. Dominated by fixed charges

LIGNITE.[3] Lignite is a fuel intermediate in composition between peat and coal. Large, accessible deposits occur in South Dakota, and there are significant deposits in seven other states. Estimated reserves are 4.07×10^{11} t representing 59 percent of the present bituminous coal reserve and 104 percent of the subbituminous reserve.[4,4a] This material is not widely used at present, although a commercial barbecue briquette[5] process is based on it, but it is potentially of great value. Some lignites contain significant amounts of uranium.

COAL. Coal is the most important of the solid fuels. Worldwide consumption is about 4×10^9 t/year with the United States consuming 7×10^8 t/year. Sufficient known U.S. reserves exist to satisfy domestic requirements for at least 200 years at the present rate of consumption, but much of this is high-sulfur coal, which causes serious air pollution. Unless the coal can be treated before, during, or after burning to reduce sulfur emissions, it cannot be used by electrical utilities or for domestic heating on a large scale. Chemical engineers continually hope that the annual shortage of oil (approximately 3×10^8 t/year) can be alleviated by the conversion of coal through commercial liquefaction and/or gasification of coal.[6] The size of such a project is extremely large, requiring creation, at gigantic expense, of an industry approxi-

[3]Mannon, Lignite Revival Takes Texas by Storm, *Chem. Eng.* 85 (7) 75 (1978); Parkinson, How to Get Water Out of Lignite, Wood, and Peat, *Chem. Eng.* 85 (7) 77 (1978).

[4]*Minerals Yearbook 1972*, Dept. of the Interior, 1974.

[4a]t = 1000 kg.

[5]*Chem. Eng.* 70 (15) 108 (1963).

mately the size of the present petroleum industry. Nevertheless, it may be done. The U.S. government is financing several small demonstration units. Here, small refers to units far larger than most chemical plants, but still small for such a huge job. South Africa has a functioning coal-to-oil business well established (Sasol).

Coals are classified, according to their fuel properties, as anthracite, bituminous, subbituminous, and lignites with subdivisions for each type. Anthracite was a valuable domestic fuel because of its clean burning characteristics, but it is now largely exhausted. The principal uses of bituminous coal are combustion for energy and carbonization (Chap. 2) for coke, tar, coal chemicals, and coke-oven gas. Table 2.1 outlines the various fields in which coal is an important raw material and the areas in which exploratory development is being undertaken. Gasified coal, as methane, low heating value gas, or high heating value gas, shows much promise as a fuel of the future and is essentially nonpolluting.[7]

Pulverized coal has been increasingly used during recent years in suspension firing for power plant installations because of the high thermal efficiency with which it can be burned, the low cost of operation and maintenance, and its great flexibility. All these factors more than balance the increased cost of preparing the fuel. In burning pulverized coal, the fly ash leaves the boiler and is carried along with the waste gases. It is removed from the flue gases by an electrostatic precipitator or other device. It has been used in bricks, building blocks, and concrete. Large tonnages of fly ash are sintered to produce a lightweight aggregate. Normally it is considered a low-valued nuisance.

COKE. Coke is a fine fuel, but it is expensive for industrial use except in blast-furnace operation, where it is a chemical reactant as well as a fuel. Coke production still parallels pig-iron production, though the amount of coke used per ton of iron continues to decrease. Other solid fuels such as coke breeze (finely divided coke dust), wood, sawdust, bagasse, and tanbark are used where they are available cheaply or where they are produced as by-products.

Liquid Fuels

FUEL OIL. The only important liquid fuel used for power generation is fuel oil. It is the fraction of petroleum crude oil that cannot be converted economically by the refiner into higher-priced products. It consists of a mixture of the liquid residues from the cracking processes and fractions with a suitable boiling point obtained by the distillation of crude oil. Fuel oils are classified by their properties, e.g., flash point, pour point, percentage of water and sediment, carbon residue, ash, distillation temperatures, and viscosity. These properties are determined by standardized tests developed under the auspices of the ASTM (American Society for Testing and Materials). The flash point indicates to a degree the safety in handling, but is relatively unimportant for determining the combustion behavior of the fuel in the burner. Oil-burning equipment usually shows higher thermal efficiency (75 percent) than coal-burning boilers and labor costs are usually less. Oil contains much more hydrogen than coal. This hydrogen burns to form water, which carries much heat out of the stack because of the high latent heat content of steam. Stack losses are nearly double those from coal combustion.

OTHER LIQUID FUELS. Other liquid fuels include tar, tar oil, kerosene, benzol,[8] and alcohol, which are consumed to a much smaller extent than fuel oil. Gasoline is consumed mainly in internal combustion engines.

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[7]Whitaker, Coupling a Gasifier to a Combined-Cycle Plant, *EPRI J.* p. 22, April 1981.

[8]The common commercial name for technical grade benzene.

Table 1.3 shows the world energy consumption and the distribution of fuels used throughout the world. The United States used 28 percent of world production of energy in 1978.

Table 1.4 shows that the United States now has a very great dependence on the Middle East for oil to supplement its domestic production of petroleum products. The 1973 to 1974 embargo was followed by a huge increase in petroleum prices. The adverse effect of this unprecedented rise and the currently unsolved problem of imbalance of payments with the Middle East continues to depress business in the United States. The effect on developing countries has been even more severe. The energy resources of the United States are considerable, but a comprehensive energy policy has not yet been formulated by the federal government despite publication of a stated policy. The direction which is to be taken to make us once again self-sufficient in energy is not now apparent. It is well-recognized that there is not an endless supply of so-called low-cost oil. Increased crude oil producing capacity will be more costly, since much of the producing capacity will come from offshore and arctic regions involving higher costs of exploration, production, transportation, and meeting stringent environmental standards.

U.S. production of crude oil and natural gas is expected to diminish slowly over the long term. Over the middle term, some scientists feel there is much yet to be discovered by searching in new areas and at greater depths. Superior techniques for recovering oil from spent fields and new scientific methods of prospecting for oil and gas are helping to slow the downward trend. Environmental objections to the use of high-sulfur fuels as well as a hardening of the public attitude toward nuclear power generation make decision making very difficult.

Proven oil reserves have been shrinking in recent years and U.S. crude production has been falling at the rate of about 3 percent per year. Even the opening of the great Alaskan fields has not greatly slowed this fall. Best optimistic estimates, taking into account new prospecting techniques and increased drilling activity, project declines of at least 1½ percent per year.

***Table* 1.3** World Energy Consumption, 1960–1979 (in metric tons of coal equivalent)

	Consumption (10^6 t)					
Region and Energy	1960	1970	1975	1977	1978	1979
United States	1447	2204	2284	2435	2452	2506
Western Europe	787	1303	1413	1492	1526	1576
Japan	96	315	354	383	381	431
Centrally planned economies*	1254	1824	2347	2597	2725	2819
Rest of world	435	866	1131	1261	1311	1374
World total	4019	6512	7529	8168	8395	8706
Energy Source						
Solid fuels	2049	2272	2397	2560	2612	2738
Liquid fuels	1293	2792	3348	3692	3768	3834
Natural gas	593	1293	1561	1666	1738	1846
Electricity	85	155	223	250	277	288

*Includes China, Dem. People's Rep. of Korea, Mongolia, Vietnam, Algeria, Bulgaria, Czechoslovakia, German Dem. Rep., Hungary, Poland, Romania, and U.S.S.R.

SOURCE: Statistical Abstract of the United States.

***Table* 1.4** U.S. Foreign Trade in Petroleum Products, 1960–1980* (in PJ, 10^{15} J)

Year	Crude Oil			Petroleum Products			Natural Gas		
	Imports	Exports	Net Trade	Imports	Exports	Net Trade	Imports	Exports	Net Trade
1960	2,316	19.0	−2,297	1900	435	−1465	170	12.7	−157
1965	2,799	6.3	−2,793	2899	407	−2496	497	28.5	468
1970	2,968	30.6	−2,938	4911	548	−4363	892	75.9	−816
1972	4,970	1.0	−4,968	5893	493	−5400	1100	84.4	−1020
1974	7,800	6.3	−7,793	6045	483	−5562	1039	82.3	957
1976	11,855	17.9	−11,836	4677	477	−4200	1042	69.6	972
1977	14,796	111.8	14,684	4987	430	−4557	1094	59.1	1035
1978	14,198	353.3	−13,844	4603	456	−4147	1050	55.9	−993
1979	14,583	524.2	−14,058	4333	533	−3800	1371	59.1	−1312
1980	11,710	634.9	−11,075	3566	584	−2982	1087	59.1	−1028

*Calculated from data in *Statistical Abstract of the United States*, 102 ed., 1982.

The fact must be faced that oil is a finite, nonrenewable resource and will ultimately be exhausted, possibly within the lifetime of persons already born.

SHALE OIL.[9] Shale oil has a potential to replace some of the petroleum being used, and the United States has large reserves. The oil in shale is chemically bound and cannot be simply solvent extracted. The U.S. Geological Survey has estimated mineable shale reserves at 1.77×10^{11} t of oil, sufficient to meet domestic consumption at the present rate for several hundred years. Small shale oil plants have been built and commercial-sized ones planned, but problems, economic and technical, are formidable. Only around 11% by weight of the shale is oil, and this oil, called kerogen, is somewhat inferior in quality to the usual petroleum crude oil. Until plants producing about 14,000 t of oil per day are constructed, shale processing does not approach petroleum refinery sizes and no plants of this size are currently projected. Unfortunately, shale oil deposits are mostly on public lands, in arid regions far from markets. Development[10] requires investments in the several billion dollar range, and environmental problems of considerable complexity accompany the disposal of the large volume of spent shale. This is, however, a resource that may be developed soon.

TAR SANDS. Tar sands contain up to 18% heavy bitumen entrapped in a matrix of sand, silt, and water. The light oil content of such sands averages less than that of oil shale, but recovery is much easier. Recovery is usually by steaming. Large deposits containing up to 14% bitumen have been identified and are being commercially developed. Athabasca (Canada) sands are estimated to contain 4.53×10^{11} t of recoverable oil. This is enough to supply the total energy requirements of the United States for 18 years at the 1980 consumption rate. Mining and removing the bitumen (tar) in an environmentally acceptable fashion under arctic conditions is proving to be difficult and not very profitable, but is proceeding.

Gaseous Fuels

NATURAL AND MANUFACTURED GAS. Natural and manufactured gas is burned as a source of heat in domestic installations and also in industry. Blast-furnace gas resulting from the smelting of iron is an outstanding example of a by-product gas employed for heating the blast stoves, with the remainder burned under the boilers or for heating coke ovens. Fuel gases are discussed in Chap. 3, where a tabulation of heating values and other properties is given.

The reserves of U.S. oil and gas are not inexhaustible. The cost involved in finding, developing, and supplying oil and gas will probably increase sharply with time. Government regulations are a major influence on the supply and utilization of natural gas. Deregulation completely alters the situation.

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[9]Frumkin, Owens, and Sutherland, Alternate Routes for Refining Paraho Shale Oil, *Chem. Eng. Prog.* 75 (9) 64 (1979); Gerry, Combined Retorting Technique for Shale Oil, *Chem. Eng. Prog.* 75 (9) 72 (1979); Duir, Griswold, and Christolini, Oil Shale Retorting Technology, *Chem. Eng. Prog.* 79 (2) 45 (1983); Dougan, The BX in Situ Oil Shale Project, *Chem. Eng. Prog.* 75 (9) 81 (1979); Kaplan, Improved Routes for Making Jet Fuels from Shale Oil, *Chem Eng.* 88 (26) 39 (1981); Taylot, Oil Shale Commercialization: The Risk and the Potential, *Chem. Eng.* 88 (18) 63 (1981).

[10]McIntyre, Giant Oil-Sands Plant Comes On-Stream, *Chem. Eng.* 85 (20) 123 (1978); Kohn, Oil Recovery Is Higher in New Tar-Sands Route, *Chem. Eng.* 87 (25) 37 (1980).

Combustion

Most modern industrial plants burn coal on mechanically operated grates or stokers or in the pulverized form. These present-day procedures allow the ratio of air to fuel to be properly controlled, thus ensuring efficient combustion and reducing heat losses through stack and ash. When fuel oil is burned, it is frequently necessary to provide heaters to lower the viscosity of the oil sufficiently for proper burner operation. The flue gas analysis is valuable in controlling combustion, since the proportions of CO_2, CO, and O_2 in the flue gas will indicate incomplete combustion or excess air.

Cogeneration

Certain chemical processes such as sulfuric acid and ammonia manufacture produce a substantial surplus of heat, available usually as medium- to high-pressure steam. At present beer manufacture, paper manufacture, and oil refining are also producing surplus steam that is converted to salable electricity and useful residual thermal energy. This is not new, but the practice is growing. There are problems in collecting and utilizing diverse small sources,[11] but efficiencies of even small units can be quite high and the Public Utilities Regulatory Policy Act of 1978 makes cogeneration very attractive economically. These sources were estimated to total 6 GW with a potential for 12 GW by 1990.

POWER GENERATION

About 1800 the first successful attempt to generate steam under pressure in an enclosed vessel was made. Since then the use of steam has increased to such an extent that today steam furnishes the major portion of the power developed in the country. The most recent developments have been toward improvements in boiler construction in central power stations, with the aim of producing higher-pressure steam. Such high pressures increase overall efficiency in the production of electric power. The limiting factor is the failure of materials at the high temperatures and pressures involved. Earlier 0.569 to 0.631 kg of the best coals were required per megajoule of energy produced, whereas currently, some power plants produce a net megajoule from 0.078 kg of coal. Figure 1.3 is the elevation of a large utility water-tube boiler.

Boilers

Standard boilers are either *water* (inside the) *tube* or *fire tube*. Large high-pressure units are water tube; smaller units for lower pressure and portable units are often the simpler fire-tube units.

Water-tube boilers are usually large stationary installations that generate steam at pressures above 1000 kPa. The water is in the tubes and can be converted to steam more quickly

[11]Wayne, Plugging Cogeneration into the Grid, *EPRI J.* p. 6, July/August 1981. Roszkowski, Grisso, Klumpe, and Snyder, Gasification in Combined/Cogeneration Cycles, *Chem. Eng. Prog.* 79 (1) 9 (1983).

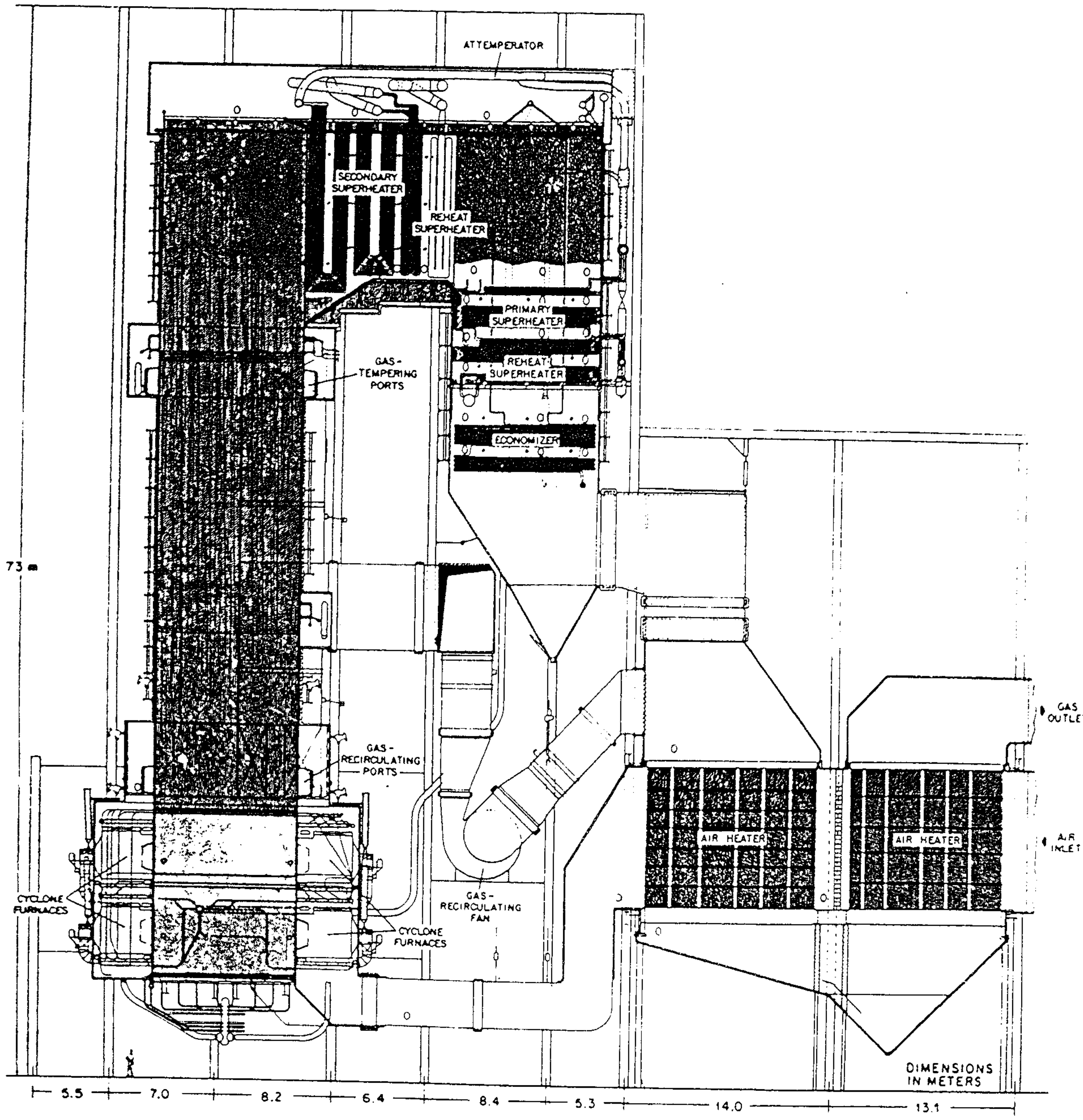

Fig. 1.3. Elevation of a large utility water-tube boiler. Capacity 2×10^6 kg/h; outlet pressure 18.1 MPa; temperature 540°C; height 73 m. *(Babcock and Wilcox Co.)*

(quicker steaming) than in a fire-tube boiler. All high-efficiency units are of this type. Boiler feedwater treatment is vital for trouble-free service. Foaming, caustic embrittlement, corrosion, and scale formation result when insufficiently conditioned water is used. Higher pressures require very carefully conditioned feedwater.

Figure 1.4 shows a portable packaged boiler that is used for generating steam at 1725 kPa and that has a capacity of 45,000 kg of saturated steam per hour.

Electric Power from Steam

Much steam is generated solely to produce electrical power. In the process industries, however, steam is used for heating vessels—usually at comparatively low pressure. This "process steam" demand is often very large in chemical manufacturing plants. Coordination and balancing the power and process steam requirements can result in major cost reduction. Large

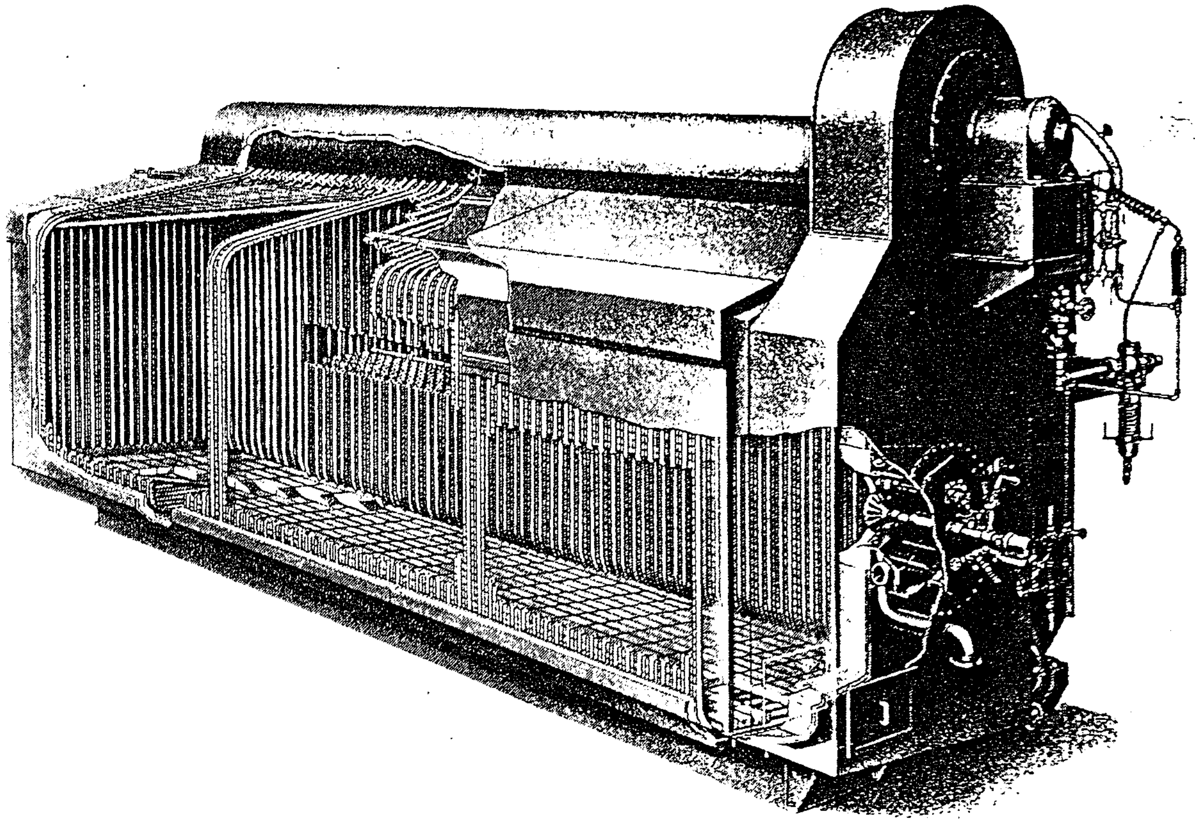

Fig. 1.4. Portable water-tube boiler *(Babcock and Wilcox Co.)*

utility generating plants generate steam at high pressures and with considerable superheat, then pass it through turbines exhausting into a vacuum produced by large condensers. This procedure extracts maximum power from the steam generated.

Superheat is very undesirable in process steam, and high pressure is usually unnecessary and unwanted. Instead of exhausting the power-producing turbine to a vacuum, saturated steam can be removed (bled off) from the turbine at the pressures and temperatures at which process steam is required. This effectively uses the turbine as an energy-efficient reducing valve. This system can save as much as 61 percent in fuel compared with a conventional system. Such systems have also been used in nitric and sulfuric acid plants to increase heat-use efficiency. One author has described a sulfuric acid plant as "a power plant that incidentally produces sulfuric acid."[12]

Balancing heat use and electrical power demand for cogeneration plants has proved to be somewhat of a problem. Superheat is necessary to prevent erosion of turbine blades, but it reduces the heat-transfer rate with process steam. Table 1.5 shows the relationship between power and heating value of steam. Turbines are ideal for chemical plants because of their flexibility as prime movers and their ability to act as efficient pressure reducers. The economies obtained by cogeneration are increasingly important in chemical process plants.

Heat Transmission Other than by Steam

Where indirect heating is necessary, some method other than steam should be used for temperatures above 200 to 230°C, where the pressure of steam becomes too high for economical

[12]Anon., The Changing Sulfuric Acid Industry, *Chem. Week* 130 (6) 40 (1982).

***Table* 1.5** Comparison of Energy from the Isentropic Expansion of Steam to an Exhaust Pressure of 20.7 kPa for Power and Heat-Transfer Processes

Sat'n. Pressure, kPa	Sat'n Temp, °C	Degrees of Superheat, °C	Vapor Temp., °C	Enthalpy, kJ/kg	Entropy, kJ/kg·K	End of Expansion			Work of Expansion, kJ/kg	Heat Available for Process, kJ/kg
						Enthalpy, kJ/kg	Moisture Content, %	Temp., °C		
2758	229	278	507	3475	7.293	2779	—	156	695	2273
2758	229	222	452	3354	7.135	2702	—	122	645	2200
2413	222	194	417	3275	7.084	2689	0.6	—	586	2182
2069	214	278	492	3452	7.394	2826	—	178	626	2319
2069	214	167	381	3205	7.043	2675	1.4	—	530	2168
1724	205	139	344	3128	7.009	2663	2.0	—	465	2156
1379	194	222	417	3291	7.361	2807	—	166	484	2300
1379	194	111	305	3052	6.980	2652	2.5	—	400	2145
1034	181	83	265	2973	6.967	2652	2.5	—	321	2145
690	164	111	275	3010	7.210	2745	—	138	265	2238
690	164	56	220	2891	6.988	2654	2.5	—	237	2147
345	138	111	250	2963	7.449	2845	—	188	119	2338
345	138	50	188	2838	7.193	2740	—	136	98	2233

SOURCE: Data computed from Keenan, Keyes, Hill, and Moore, *Steam Tables—Thermodynamic Properties of Water Including Vapor, Liquid, and Solid*, Wiley, New York, 1969. Superheated steam is used to prevent erosion of turbine blades caused by droplets of moisture in the steam.

design of the plant. Steam owes its importance as a heating medium to its convenience and cleanliness, but particulary to its large heat of condensation. Where conditions lie outside the range of steam, the engineer turns progressively, as the temperature rises, to other means such as:

Method	Temperature °C	Remarks
Direct firing	Above 150	Low cost and convenient but a fire hazard
Indirect firing	Above 150	Low operating cost but elaborate setting and a fire hazard
Direct gas heating	Above 150	Moderate cost and excellent control but a fire hazard.
Hot oil	150–315	Good control but high first cost and oil carbonization problems.
Dowtherm	204–400	Good control and moderate operating cost but higher first cost
Mercury vapor	315–650	Good control and moderate operating cost but highest first cost
Mixed salts	120–480	Good control and good heat transfer at high temperature
Electricity	Above 150	Most accurate control but operating cost usually high

Direct or indirect heating with coal or gas is frequently surprisingly efficient when the furnace is well designed; however, the open flame is a fire hazard. Under conditions where oil is not carbonized, this heat-transfer medium has been so widely employed that furnaces for heating the oil and equipment for the heat transfer are both available on the market as standardized and tested designs. Dowtherm (diphenyl 26.5%, diphenyl oxide 73.5%, eutectic mixture) is stable at higher temperatures than oil and has the added advantage that it can be employed as a vapor, where its latent heat of condensation can be used as well as its sensible heat. Other temperature-stable oils and chemicals are being used as high-temperature heat-transfer media. Mercury has been successfully used in controlling the heat of reaction in reactors, but it is extremely heavy and its vapors are poisonous.

For years mixtures of inorganic salts have been accepted as heat-transfer media, but the modern large-scale demand for such salts to remove heat from petroleum cracking processes such as the Houdry catalytic one was necessary to justify a careful study of the properties of the mixed salt consisting of approximately 40% $NaNO_2$, 7% $NaNO_3$, and 53% KNO_3. Tests indicated no danger even when a stream of hot petroleum was injected into the molten nitrate-nitrite bath. Electricity in contact, immersion, and radiant heaters is a most convenient, accurate, safe, and efficient heating medium though it is generally costly.

Nuclear Energy

There exist only two generally accepted possibilities for meeting increasing energy needs during the next 20 years, coal and nuclear fission. Both possess disadvantages that generate public concerns. For a unit of power produced, coal plants release more radioactivity than nuclear plants of similar capacity. Sulfur dioxide pollution is believed to be the cause of "acid rain" (precipitation with a low pH due to air constituents). Some lakes show recent decreases in pH believed due to such acid rain. Nuclear power is nonpolluting, but the absence of visible and tactile effects causes great concern in some quarters. Harm to human beings as a result of

nuclear power plant emissions has not yet been reported. Proven uranium reserves are sufficient to last until the turn of the century if used in fission reactors on a once-through basis. Breeder reactors increase the recovery by a factor of at least 100, making the supply of fissionable material sufficient for power demands for 100,000 years if all possible fuels are properly used and recycled.[13] The National Academy of Sciences has recommended that "national policy should support the continued use of nuclear power for the next few decades."

The United States led the world into the nuclear age, but vascillating public policy and objections by vociferous minorities have caused it to fall behind other countries in adopting nuclear power production and have put the whole domestic nuclear program in doubt. Twelve percent of domestic power, equivalent to 2.08×10^5 m^3 of oil per day, was derived from nuclear fission in 1980.[14] It is difficult to see how the country can meet its immediate needs without using nuclear power.

Worldwide nuclear power is a major source of energy, and its production is rapidly increasing. The United States is not able to set world policy, so nuclear power will probably develop rapidly on a worldwide scale without U.S. influence. As of 1981, 241 nuclear power plants were in commercial operation, and 535 more were either under construction or authorized. These plants will produce 408,100 MWe, 244,600 outside the United States. Table 4.6 shows the current distribution of power plants.

Hydroelectric Power

Many chemical industries require large amounts of low-cost electrical power for their operations. Hydro power, developed in times when capital and interest costs were low, is frequently very inexpensive, but most large sources in the developed countries have been exploited, and small units produce electricity at higher cost. Hydroelectric plants must be situated where a head of water is available from a waterfall or a dam. This water is used to drive a turbine attached directly to a generator. The initial cost of a hydroelectric plant is much greater than that of a steam plant of identical size, but the operating cost is far lower.

OTHER POSSIBLE SOURCES OF ENERGY (Alternate Energy Sources)

Biomass

Wood, bagasse, and similar biomass[15] materials have been important home heating fuels since ancient times. A few industrial operations operate on wood waste or sawdust. Despite the extreme pollution that characterizes wood combustion, it is being touted for space heating. It

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[13]National Academy of Sciences, *Energy in Transition 1985-2010,* Freeman, San Francisco, 1979.

[14]*Two Energy Futures: A National Choice for the Eighties*, American Petroleum Institute, Houston, Tex., 1980.

[15]Calvin, The Sunny Side of the Future, *CHEMTECH* 7 (6) 352 (1977).

***Table* 1.6** World Nuclear Power Plants Operable, Under Construction, or On Order as of June 30, 1981

	Authorized	Operating		Authorized	Operating
Argentina	3	1	Mexico	2	0
Austria	1	0	Netherlands	2	2
Belgium	7	3	Pakistan	1	1
Brazil	3	0	Philippines	1	0
Bulgaria	4	3	Poland	2	0
Canada	24	10	Romania	3	0
Czechoslovakia	11	3	South Africa	2	0
Egypt	1	0	Spain	18	3
Finland	4	3	Sweden	12	8
France	59	26	Switzerland	7	4
German Democratic Republic	7	5	Taiwan	6	2
German Federal Republic	29	11	United Kingdom	42	32
Hungary	4	0	United States	172	72
India	10	4	U.S.S.R.	41	29
Italy	9	4	Yugoslavia	1	1
Japan	35	13	World total	535	241
S. Korea	9	1	Non-U.S.	363	1169
Libya	1	0			
Luxemborg	1	0			

is doubtful that any large-scale use of biomass materials can come about, particularly because the land that would be used for its growth is more desperately needed for agriculture.

Geothermal Energy

While the present applications of geothermal energy make only a small contribution to the world's total energy generation, there were 85 units in operation[16] in 11 countries in 1981. These had an installed capacity of 1759 MW with 1830 MW more planned or under construction for completion in 1982. Iceland, Italy, Mexico, New Zealand, and the United States have commercial stations operating. The largest has a capacity of 500 MW. Several types of units have been devised and operated, including a dual-binary system using isobutane and propane as the secondary fluids. The techniques are well established, but as yet geothermal fields with extensive enough areas to be widely useful as proven sources have not been delineated.

Wave and Tidal Energy

In areas where large tides occur, the possibility of producing modest amounts of power exist. The French have created a successful operating unit. Low head and intermittent operation makes such units unattractive. Invention of a high-density cheap storage system could help in the development of tidal, solar, and wind energy. Wave energy awaits development of effective and efficient energy transducers.

Fuel Cells

These devices, which generate electricity without moving mechanical parts, have very interesting possibilities. Their theoretical possibilities have been understood for a long time, but practical units have become possible only recently, and even today the requirement of very clean fuel limits their scope. A fuel cell is a device substantially without moving parts, in which a fuel, such as hydrogen, natural gas, methanol, or propane, can be converted directly into twice the quantity of electrical energy that would result from the usual boiler-turbine-generator combination. Efficiencies are 40 to 80 percent, versus the usual 25 to 40 percent.

The fuel cell differs from the storage battery in that usually its gaseous or liquid fuel and its oxidizer are led in from outside, whereas the storage battery stores its solid fuel and oxidizer on plates where they are consumed. A fuel cell[17] operates electrochemically or, more literally "chemicoelectrically," as shown in the cell diagrammed in Fig. 1.5. This cell is actually a reactor wherein hydrogen as the feed stream or fuel is conducted into the empty space paralleling the porous, electrically conducting anode. This anode can be made of porous carbon with a metal catalyst such as platinum, which chemically changes the hydrogen atoms to positively charged hydrogen ions and electrons. The electrons leave the anode, perform

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[16]DiPippo, *Geothermal Energy as a Source of Electricity,* Supt. of Documents Stock No. 061-00-00390-8, 1980; There's a Boom in Geothermal Power, *Chem. Week* 130 (26) 29 (1982).

[17]Sweeney and Heath, *Fuel Cell: Its Promise and Problems,* API, Houston, Tex., May 9, 1961, Parkinson, Fuel Cells' Prospects Are Getting Brighter, *Chem. Eng.* 90 (2) 30 (1983).

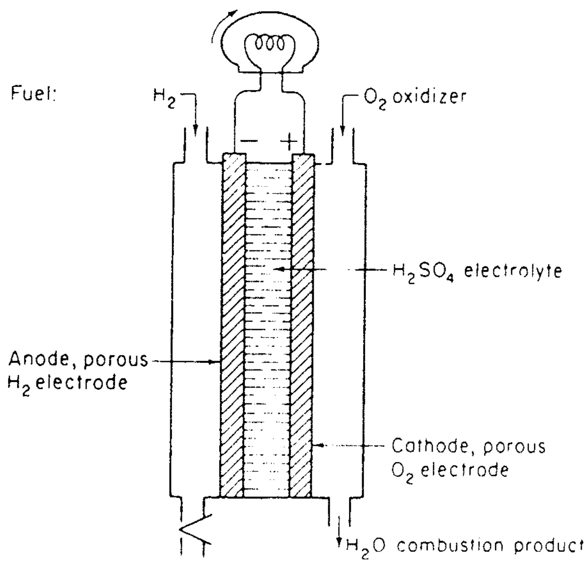

Fig. 1.5. A hydrogen-oxygen fuel cell in which the current is carried internally via mobile hydrogen ions. (Sweeney and Heath[17])

work, and enter the cathode (Fig. 1.5). Meanwhile the positively charged hydrogen ions migrate through the electrolyte (for instance, 50% KOH or H_2SO_4) attracted by the oxygen from the cathode. To complete the reaction, the oxygen pulls in the electrons also, and water is generated and discharged from the cell. The cell is so arranged that the electrons must move up the anodes, leave the cell through a wire, and enter the cell again at the cathode. While the electrons are outside the cell, they form the electric current and do work

$$H_2 \xrightarrow{\text{anode}} 2H^+ + 2e$$

$$O_2 \xrightarrow{\text{cathode}} 2O$$

$$2H^+ + O\ (\text{or } \tfrac{1}{2}O_2) + 2e \rightarrow H_2O$$

Cell overall:

$$H_2(g) + \tfrac{1}{2}O_2(g) \xrightarrow[\text{2 electrons}]{25°\text{C, 101 kPa}} H_2O(l) \qquad \Delta E = -237 \text{ kJ}$$

$$H_2(g) + \tfrac{1}{2}O_2(g) \xrightarrow{25°\text{C, 101 kPa}} H_2O(l) \qquad \Delta H = -286 \text{ kJ}$$

$$\text{Theoretical efficiency} = \frac{237}{286} \times 100 = 82.9 \text{ percent.}$$

The decrease in free energy indicates that the hydrogen and oxygen will react more readily; the fuel cell provides a mechanism for this. Hydrogen-oxygen fuel cells have been operated at about 25°C, but a single cell produces about 1 V of direct current, so many cells are needed in series to produce useful voltage.

In many places in the United States it is much cheaper to use natural gas or propane in fuel cells than to purchase generated electricity. It is also much cheaper to use air rather than oxygen for the oxidizer. Many other chemicals are being studied for use in fuel cell operation. One form of current interest uses the oxidation of methanol to formic acid. The questions to be resolved are relative costs and the actual design of an efficient cell. The fuel cell is one of the most interesting devices for the production of useful energy now being investigated.

Figure 1.6 shows an example of a commercial fuel cell that achieves an efficiency above 40 percent in generating electricity. If such a unit could be placed where the waste heat generated could be used for space heating (offices, apartment houses, homes), thermal efficiencies of over 80 percent could be obtained. Electrical transmission costs are also reduced when the generating system is very near the consumer. Because such units are quiet and nonpolluting, they can be placed in residential areas. A considerable number of these units are being built, installed, and tested.

Solid Waste Energy

Particularly in the United States, large amounts of trash and garbage are generated and disposal is a major problem. Several cities are now burning trash and garbage to generate steam and electricity. Results appear to be quite satisfactory, although refuse-derived fuel (RFD) has been unsatisfactory for some installations. Air pollution must be carefully avoided, but this use of waste is very desirable. Table 1.7 shows the heating value of waste materials.

[18]Porteous, *Refuse Derived Fuels*, Wiley, New York, 1981

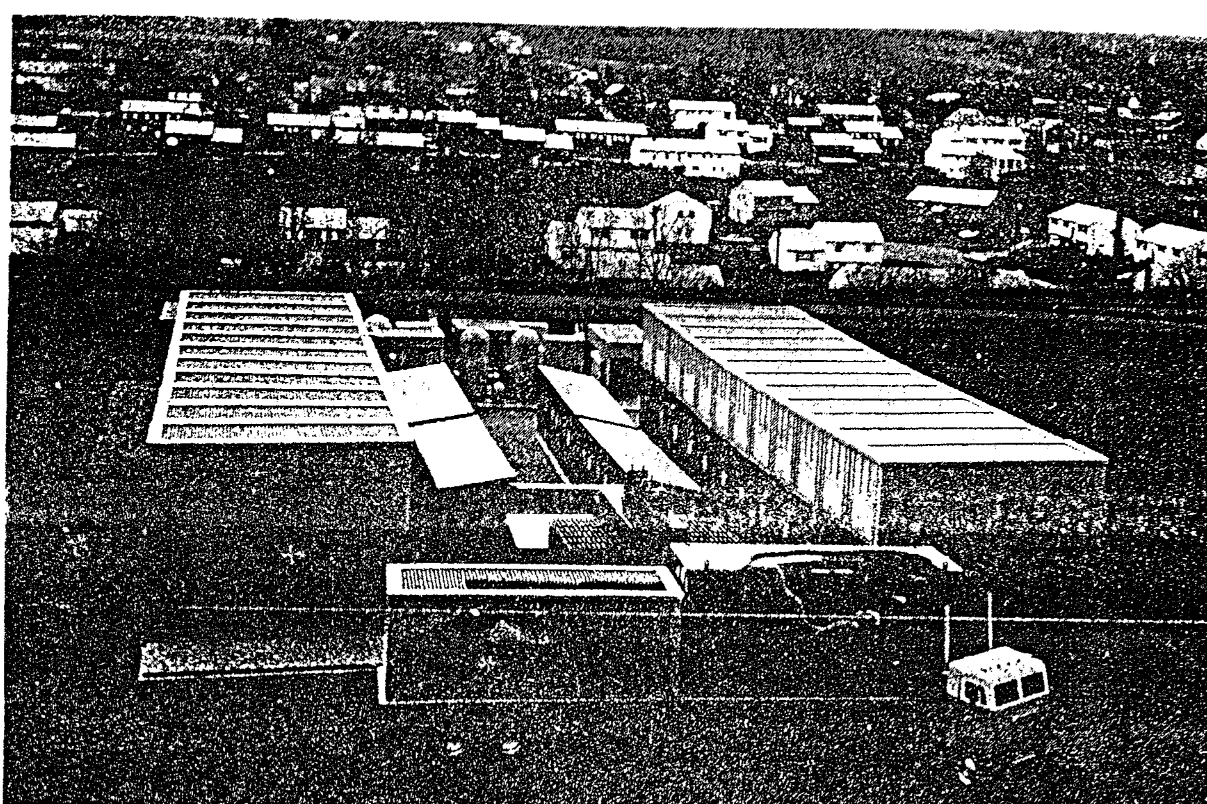

Fig. 1.6. Model of United Technologies' 26-MW dispersed generator under development for electric utility application, which was designed to generate electricity at 40 percent efficiency. It uses naphtha fuel. *(United Technologies, Power Systems Div.)*